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Medium Access and Data Link Layer Protocols for Impulse Radio: Covertness, Timing, and Chip Discrimination

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13. ABSTRACT (Maximum 200 words)

Ultra-Wideband (UWB) impulse radio (IR) has been shown to have potential for dramatic throughput in high multi-user environments everaging the ultra-wideband nature of sub-nanosecond pulses. Many of the IR attributes hold promise for tactical systems where low power covert operation is desirable.

In this project we have investigated three areas related to impulse radio: covertness, the effects of timing jitter and synchronization, and a new chip discrimination technique that expoits the narrow pulses and low duty cycle of impulse radio. Advances in these areas are important for medium access control (MAC) layer design.

We quantify the covertness of impulse radio and find its detectability is superior to other narrow band systems even when a sophisticated "multi-radiometer" detector is used. We also quantify the effects of timing and tracking errors on the performance of impulse radio. A new chip discrimination technique for impulse radio is investigated. The technique provides significant improvement in multi-user environments and is very simple to implement.

14. SUBJECT TERMS
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Sincerely,

Keith Townsend

Final Progress Report: "Medium Access and Data Link Layer Protocols for Tactical Impulse Radio Networks: Covertness, Timing, and Chip Discrimination", J. K. Townsend, W. M. Lovelace, A. Bharadwaj

(1) List of Papers Submitted or Published During Reporting Period

Published in a Journal: W. M. Lovelace, J. K. Townsend, "The Effects of Timing Jitter and Tracking on the Performance of Impulse Radio", *IEEE Journal on Selected Areas of Communications*, vol. 20, no. 9, pp. 1646–1651, Dec., 2002.

Published in Conf. Proc.: A. Bharadwaj, J. K. Townsend, "Evaluation of the Covertness of Time-Hopping Impulse Radio Using a Multi-Radiometer Detection System", *Proceedings of Milcom 2001*, Vienna, VA, October, 2001.

Published in Conf. Proc.: W. M. Lovelace, J. K. Townsend, "The Effects of Timing Jitter on the Performance of Impulse Radio", *Proceedings of IEEE Conference on Ultra Wideband Systems and Technologies*, May, 2002.

In review: Journal: W. M. Lovelace, J. K. Townsend, "Chip Discrimination and Blanking for Large Near Far Power Ratios in UWB Networks", submitted to the *IEEE Transactions on Communications*, March, 2003.

In review: Conference: W. M. Lovelace, J. K. Townsend, "Chip Discrimination for Large Near Far Power Ratios in UWB Networks", submitted to the *IEEE MILCOM 2003* , March, 2003.

(2) Scientific Personnel Supported, Honors and Awards during Reporting Period

- Arjun Bharadwaj, Awarded the MS degree, December, 2002.
- William M. Lovelace, PhD candidate, (has completed 1/2 of his research program, and all of his course work.)

(3) Scientific Progress and Accomplishements

Ultra-Wideband (UWB) impulse radio (IR) has shown the potential for dramatic throughput in high multi-user environments leveraging the ultra-wideband nature of sub-nanosecond pulses [1, 2]. Many of the IR attributes hold promise for tactical systems where low power covert operation is desirable. Such covert systems deployed in a standalone peer-to-peer network may take advantage of the low power and duty cycle of IR to provide modest throughputs with very low power spectral densities [3, 4]. While extremely high multi-user densities are possible with IR, the tactical application may require leveraging potential system bandwidth for covert power levels and overall low power consumption. Many considerations apply to the design of such standalone covert IR systems such as assumed pulse densities, peak and average pulse power levels and complexity.

Impulse radio has been analyzed under a number of conditions including equal power multi-user environments with binary signaling [1, 2], M-ary signaling [5], and dense multipath

[6]. Some medium access control (MAC) layer issues such as power control and peer-to-peer architectures specific to issues related to a covert impulse radio network have been investigated [7, 8, 9].

In this project we have investigated three areas related to impulse radio: covertness, the effects of timing jitter and synchronization, and a new chip discrimination technique that expoits the narrow pulses and low duty cycle of impulse radio. Advances in these areas are important for medium access control (MAC) layer design.

We quantitatively evaluate the covertness of impulse radio using a radiometer detection scheme ideally suited for detection of time-hopping, impulse radio signals [4]. The more complex detection system that we consider utilizes multiple wide band radiometers with outputs that are OR'ed and compared to a threshold. This "multi-radiometer" detection system is used to quantify covertness for single and multiple user configurations. We also evaluate covertness for cases where the detector incorporates varying amounts of prior knowledge about the impulse radio signals.

The covertness is determined for the optimal single user case, when the detector has complete knowledge about the bandwidth and the pulse width of the system, as well as the sub-optimal single user case when the detector has little prior knowledge about the impulse radio system specifications. In addition, the covertness of impulse radio is compared with that of conventional direct sequence Code Division Multiple Access (CDMA) schemes for which the covertness is calculated by well documented analytical expressions. Also considered are multiple user scenarios where the covertness is evaluated when multiple user pulses overlap as well as the case when the pulses are non-overlapping. We also determine the "average covertness" of impulse radio for a specified number of users is determined and then compared to DS-CDMA schemes with equivalent number of users.

Another area of investigation in this project is timing jitter and synchronization of impulse radio signals. This is an important issue to IR that has not been considered in the literature and requires a serious design budget consideration. The reduced complexity and other implementation advantages offered by IR in terms of filtering and linearity are somewhat offset by more stringent timing tolerances. We have been investigated the effects of timing jitter and tracking errors on the performance of IR [10, 11]. The implications of timing errors on IR performance are more pronounced since IR is based on the transmission of very narrow pulses. Only recently have clocks with reasonable stability and lower power consumption suitable for UWB systems been reported [12]. The jitter reported in [12] is on the order of 10 ps, and clock stability is only one component of the total system jitter budget. Even with very stable clocks, there are other contributions to the total jitter budget including tracking and relative velocities between transmitter and receiver.

Results of our simulations for binary and 4-ary signaling illustrate the sensitivity of IR to timing errors. Overall throughput degradation and design considerations associated with these errors are considered. The eventual throughput, power budget and complexity for an IR system are closely coupled to clock stability and tracking. We also investigate the tradeoff between binary and 4-ary signaling, and find that in the presence of timing errors, 4-ary signaling outperforms binary signaling over a wide range of operating parameter values.

Another important source of timing jitter we are investigating is tracking error [13, 14, 15]. Even without clock jitter at the sources, the noise introduced at the timing tracker jitter the sample timing. The MAC layer of a peer-to-peer network must track and maintain

relative drift rates of each link and offset the receiver clock. Compensation for these effects do not prevent the interference noise in the filtered tracker from causing jitter on the receiver window.

The narrow pulses used in impulse radio place stringent requirements on timing. In this project we have investigated the effects of timing jitter and tracking on the performance of binary and 4-ary impulse radio systems over a range of pulse interference levels. For a fixed bit error rate, we quantify relationships between the number of multi-access users and RMS jitter. The results show that system throughput degrades markedly for relatively modest increases in jitter. For the parameters used in our studies, we find that 4-ary PPM outperforms binary signaling for timing errors greater that 40 ps, even when power levels are very close to the thermal noise floor. An early-late gate tracker is implemented to show one of the familiar contributors to overall link budget jitter. Results of the simulation show tracking jitter contributions of 10 ps RMS for thermal noise and pulse densities consistent with 10^{-3} BER environments.

We have conducted a preliminary investigation of a chip discrimination technique [16, 17] for use with Impulse Radio that improves performance for large near/far interference ratios. A typical spread-spectrum IR that employs a matched filter sum for bit decisions will be susceptible to small numbers of large power pulses that can dominate the bit decision threshold statistics. This investigation focused on a technique for receiver chip discrimination prior to the spreading summation that can greatly reduce the effects of large near/ far interferers. A statistical model was developed that predicts bit error performance for binary offset PPM as a function of near/ far density and power for varying discrimination thresholds. We show that even a small number of very near interferers can greatly reduce the performance of a system without blanking or discrimination. In addition, substantial improvement using this method for near interferers with near/ far power ratios greater than 20 dB. A simple chip discrimination technique is one clear example of the benefit of the low duty cycle modulation only possible with impulse radio.

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